responsive to the needs of the NRC and DOE.

Chou says that another way the FESSP can make a significant contribution is to address the growing national consensus that a more integrated view of nuclear power is needed to effectively solve complex issues such as waste management. He notes that Tom Isaacs, head of Livermore's Policy, Planning, and Special Studies, is making a start on meeting that challenge. With FESSP help, he is working on a systematic approach for dealing with all issues related to nuclear materials use and management.

Chou also expects that the FESSP's partnerships with colleagues from other nations will continue to grow. Although the U.S. has no new nuclear power plants planned, other nations are building new plants at a very rapid rate. Japan, for example, has a vigorous nuclear power development program.

"Other countries turn to the U.S. for advice on nuclear safety," says Chou. "We can provide that advice. For our part, working with them helps the U.S. keep current with state-of-the-art nuclear technology."

The federal government has long relied on FESSP for scientific expertise, says Chou. "We're confident we'll continue to earn their trust."

— Arnie Heller

Key Words: Argus, FESSP, nuclear fuel cycle, nuclear power, Nuclear Regulatory Commission (NRC), nuclear safety, Nuclear Systems Safety Center (NSSC), nuclear waste, plutonium disposition, United States Enrichment Corporation (USEC), uranium enrichment, Yucca Mountain.

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About the Engineer

MARK STRAUCH came to Lawrence Livermore from the University of Michigan, where he received his B.S. and M.S. in electrical engineering in 1976 and 1978. An electrical engineer, he joined the Electronics Engineering Department to work on the Magnetic Fusion Energy Program. Since then, he has also supported the weapons program and O Division and was an Engineering group leader and division leader. He became deputy program leader of the Fission Energy and Systems Safety Program and assistant deputy associate director in the Energy Programs Directorate three years ago. Strauch is an active member of the Institute of Electrical and Electronics Engineers and currently is financial chair of the San Francisco Bay Area Council.

The Microtechnology Center

When Smaller Is Better

From thin-film windows to microactuators to photonic devices—the Center contributes to stockpile stewardship, bioscience, and nonproliferation projects at Livermore.

A dime-sized amplifier makes fiber-optic communications faster and clearer. A portable DNA analyzer helps detect and identify organisms in the field, including human remains and biological warfare agents. A tiny gripper inserted in a blood vessel treats aneurysms in the brain to ward off potential strokes. What do these technologies have in common? Each one is smaller than any comparable product, opening up a host of new applications. And each originated in Lawrence Livermore National Laboratory's Microtechnology Center.

In the late 1960s, Livermore scientists and engineers began making miniature devices for high-speed diagnostic equipment required for nuclear tests. For many years, before the development of Silicon Valley and the ready availability of microchips for a broad array of uses, Laboratory engineers fabricated chips to their own specifications for high-speed switches, high-speed integrated circuits, and radiation detectors. By the early 1980s, Livermore was fabricating thin-film membranes for use as x-ray windows in low-energy x-ray experiments, as x-ray filters, as debris shields for the Extreme Ultraviolet Lithography Program, and as targets for high-energy electron experiments in which x rays are generated.

These passive microstructures have been applied to dozens of projects. They have served as diagnostic devices for Livermore's Nova laser experiments and will do the same for experiments at the National Ignition Facility (NIF). Another microstructure, a novel thin-film window developed by Glenn Meyer and Dino Ciarlo, plays a critical role in a new, more efficient electron-beam system for processing inks, adhesives, and coatings. Laboratory scientists, led by Booth Myers and Hao-Lin Chen, teamed with American International Technologies Inc. of Torrance, California, on this project and won an R&D 100 Award in 1995. Conventional electron-beam processing systems are inefficient, delivering about 5% of the beam's energy to the polymer being cured. With this new window, efficiencies greater than 75% were achieved. The team also recently won a 1997 Federal Laboratory Consortium Award for Excellence in Technology Transfer.

In the mid-1980s, Livermore began combining micro-optical devices with microelectronics for extremely high-speed, fiber-optic data transmission. Photonic devices have since found their way into many microtechnologies that incorporate optical fibers for transmission of laser light.

Livermore stopped fabricating silicon-based electronic circuits when commercial microchips became available in almost every configuration imaginable. But invention by no means stopped. Today, the Microtechnology Center, now headed by physical chemist and engineer Ray Mariella, invents and applies microfabricated components, including photonic devices, microstructures, and microinstruments, to directly support Laboratory projects in science-based stockpile stewardship, nonproliferation, and biomedical research. At any given moment, the Center has about 25 projects in the works. The Center's major recent and ongoing projects are highlighted here.

The Center's state-of-the-art fabrication facilities are centered in a building whose location was selected because the area had the smallest vibrations within the Laboratory site, permitting the high-resolution microlithography that the Center performs. Microdevices can be fabricated there in any of three material systems:

- Silicon and silicon compounds for microstructures and microelectro-mechanical systems applications.
- Gallium-arsenide for photonics applications.
- Lithium niobate for electro-optic applications, such as phase and amplitude modulators.

The Center has the equipment and infrastructure needed for lithography, etching, diffusion, wafer bonding, and thin-film deposition and vacuum techniques. Its dry laboratories are used for surface inspections, packaging, and electrical and optical device testing. Groundbreaking recently took place for an addition that will increase clean-room space by 65%. The backbone of the Center is an interdisciplinary group of about 50 electronics, mechanical, chemical, and biomedical engineers, physicists, and technical support personnel (Figure 1). According to Mariella, "Ideas, technologies, and capabilities are shared at frequent brainstorming sessions, so staff can find solutions to programmatic problems quickly."

Putting Light to Work

Photonics work at Livermore got its start from the need to obtain remote, highly accurate measurements at nuclear weapons tests. Photonic systems—which manipulate and exploit light for control, communication, sensing, and information display—were the ideal solution because signals can travel on them for long distances at the speed of light with very little power loss. After several years of development, Livermore successfully fielded its first photonic system for measurement of ionizing radiation from a nuclear weapon at the Nevada

Figure 1. Most members of the Microtechnology Center staff.

Test Site in 1989. This system made available very high-resolution data that conventional measuring techniques could not deliver. In 1991, Livermore was awarded the DOE Weapons Excellence Award for this work.

A photonic network is typically made up of optical fibers, waveguides, amplifiers, receivers, wavelength selection elements, and modulators, sometimes all on a single chip. One of the Laboratory's contributions to the photonics field has been its novel application of silicon micromachining capabilities, which have been critical to packaging photonic components in a cost-effective manner. In 1994, Mike Pocha, Dan Nelson, and Ted Strand won an R&D 100 Award for the development of a silicon "microbench" that reduces the time needed to align and connect the optical fiber in photonic components. Because of the submicrometer alignment tolerances, the standard manual process was extremely time consuming and therefore expensive. The team's technique (Figure 2) provides just enough heat to melt the microdrops of solder needed to make the connection, allowing a rapid manual alignment and connection of the fiber to a laser diode or a lithium niobate modulator in less than five minutes and reducing the cost for this work by 90%.

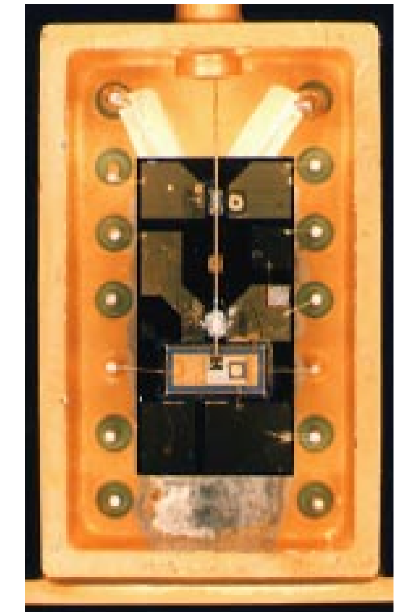

Figure 2. With the silicon microbench, two polysilicon heating elements and gold solder attachment bases provide the means for attaching the optical fiber. While the fiber is held in position, current is passed through the heater to reflow the solder, which wicks around the metalized fiber without disturbing the alignment. This new method avoids thermal shifts and simplifies the alignment process.

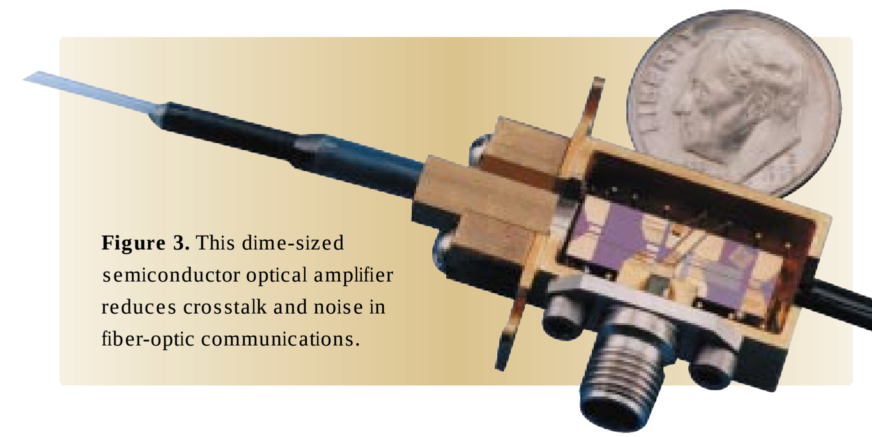

Figure 3. This dime-sized semiconductor optical amplifier reduces crosstalk and noise in fiber-optic communications.

Photonic devices are finding their way into two different parts of the Laboratory's science-based stockpile stewardship program. One is ultrascale computing, which soon will be used for simulations of nuclear tests; the other is diagnostics for NIF.

Computing on a large scale requires the cooperative action of thousands of microprocessors sharing tremendous volumes of data. This data sharing demands a communication "fabric" of very high bandwidth and low latency (short time delay) to enable the microprocessors to function without waiting for data. Optical fibers are an ideal medium provided that the optical signals are sufficiently amplified so that there are enough photons to go around for the many receiver nodes. Existing amplifiers had problems: erbium-doped fiber amplifiers are bulky and expensive, and conventional semiconductor optical amplifiers produce too much crosstalk at transmission rates above 1 gigabit per second.

To solve this problem, Sol DiJaili, Frank Patterson, Jeff Walker, Robert Deri, William Goward, and Holly Peterson developed a miniature, low-cost semiconductor optical amplifier (Figure 3). They applied state-of-the-art microfabrication techniques including molecular beam epitaxy to grow device wafers and chemically assisted ion-beam etching to make the device structures. The team won a 1996 R&D 100 Award for their new device, which can be used not only for computer interconnections but also in wide-area networks and for transmitting visual images.

They then replaced the standard gain medium inside the waveguide of the amplifier with a tiny vertical-cavity surface-emitting laser and took advantage of some basic laser properties to reduce crosstalk by a factor of 10,000. The photons' stimulated emission in the gain medium when lasing occurs acts as a clamp on the signal gain, eliminating the fluctuation. Signal channels at multiple optical wavelengths can pass through the waveguide with virtually no crosstalk among these channels. The lasing action also speeds recovery time of signals through the waveguide, from a billionth of a second to about 20 trillionths of a second. Thus, the amplifier can successfully track the amplification of a serial bit stream at very high bit rates.

The Microtechnology Center is also applying photonics technology at NIF. Because NIF's 192 laser beams will be aimed at such small targets (about the size of mustard seeds), NIF will need much faster radiation diagnostics than those used at the Nevada Test Site. Mike Pocha and Howard Lee are developing photonic radiation sensors that will modulate an optical beam in response to an ionizing radiation input and then record it using single-shot optical samplers having a response time of 100 femtoseconds (quadrillionths of a second). Pocha and Lee are investigating the use of waveguides made of nonlinear optical material to perform the extremely high-speed signal gating required to sample at these high data rates. (A nonlinear optical material is one whose index of refraction can be changed by the introduction of another light beam.) These nonlinear gates will be capable of switching sequential slices of the radiation-modulated optical signal into an array of relatively slow-speed optical detectors. A material that may have the right nonlinear properties is fullerene (C_{70}), whose discoverers recently won the Nobel Prize in Chemistry. (Fullerene is a van der Waals crystal with molecules shaped like Buckminster Fuller's geodesic domes, hence its name.) The world's first fullerene waveguide array, which is still undergoing development, is shown in Figure 4. Work continues on this project so that a fully functional system will be on line in time for the testing of NIF, which is scheduled for 2002.

Analyses in Miniature

Analyzing DNA, testing for HIV, and identifying pathogens and poisons used in biological and chemical warfare all require sampling a range of products. Supporting the Laboratory's bioscience research program and its nonproliferation efforts, the Microtechnology Center has developed several cutting-edge microdevices that facilitate biological and chemical sampling and analysis in the field, allowing real-time detection. Because some samples cannot survive transport from the field to a remote laboratory, field analysis is often the only solution.

Biological and chemical sampling with micro-instruments offers other advantages as well. Smaller instruments have lower power requirements. Highly integrated and automated sample handling systems usually result in improved productivity and less sample contamination. Also, because analytical diagnostic procedures sometimes produce hazardous wastes, smaller systems mean less waste. However, extremely small-volume chambers require greater sensitivity in order to identify the extremely small trace samples.

A team led by Ray Mariella has patented a new system that eases alignment and increases the accuracy of flow cytometry. Flow cytometry is a powerful diagnostic tool used to characterize and categorize biological cells and/or their contents, such as DNA. It is used by laboratories throughout the world for blood typing and for testing for a wide variety of diseases and viruses, including HIV. The cells flow in single file in solution while the experimenter directs one or more beams of laser light at them and observes the scattered light, which is caused by variations in the cells or DNA. Instead of using a microscope lens or an externally positioned optical fiber as a detector, Mariella's system uses the flow stream itself as a waveguide for the laser light,

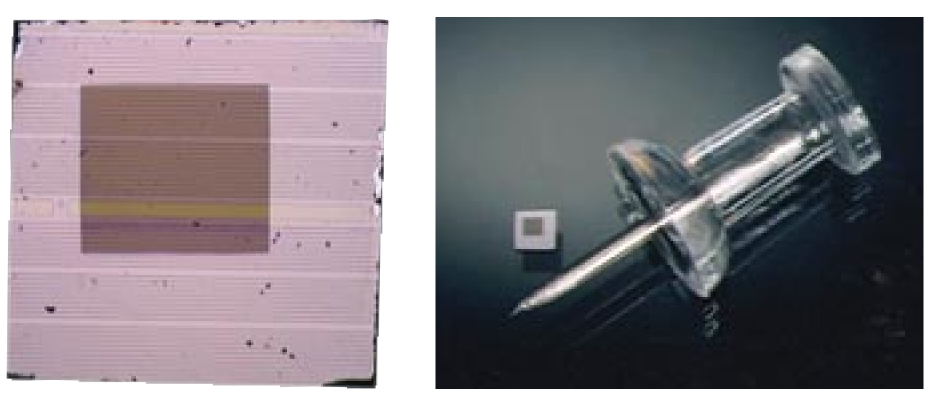

Figure 4. This fullerene waveguide array will be part of a photonic radiation sensor system at the Laboratory's National Ignition Facility. (The waveguide was photographed next to a push pin to indicate scale; the waveguide on p. 11 is between two X-acto knife blades.)

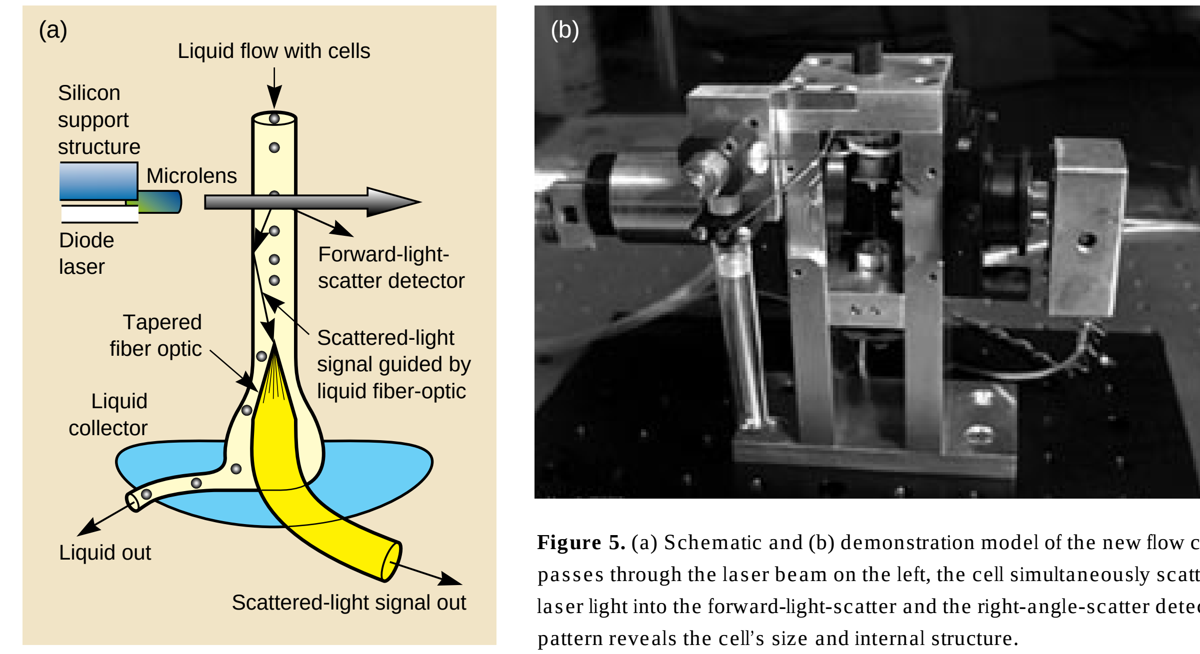

Figure 5. (a) Schematic and (b) demonstration model of the new flow cytometer. As a cell passes through the laser beam on the left, the cell simultaneously scatters (reflects) the laser light into the forward-light-scatter and the right-angle-scatter detectors. The scatter pattern reveals the cell's size and internal structure.

capturing the light and transmitting it to an optical detector. Alignment simply requires lining up the light source onto the flow stream and placing the detector into the same stream (Figure 5). With this system, measurements are up to three times as accurate as those taken with conventional systems.

At international joint field trials last fall at Dugway, Utah, the new flow cytometer performed extremely well detecting simulated biological warfare agents. Participants from the U.S., the U.K., Canada, and France used a variety of instruments to detect four simulants. The Livermore flow cytometer detected 87% of all the unknowns with a false positive rate of just 0.4%.

Dino Ciarlo, Jim Folta, and William Benett developed a miniature sample injector that can be used in Mariella's flow cytometer. Flow channels are formed by etching three silicon wafers and bonding them into a single chip. Fluidic connections are made to this injector chip via a plastic block. A thin gasket, laser-cut from an elastomeric material, forms a seal between the silicon chip and the block. The front edge of the silicon chip remains exposed to allow fluid to freely exit through an edge port into the optical detection system.

A Laboratory team headed by M. Allen Northrup has developed an portable DNA analyzer that is small enough to fit in a briefcase. It is also fast (Figure 6). This unit, the world's only battery-powered DNA analyzer, moves analysis out of the laboratory for the first time. Folta and Benett developed a disposable polypropylene liner for the analyzer's tiny heated chamber where the polymerase chain reaction occurs. The liner facilitates rapid reuse of the chamber and eliminates tedious cleaning and possible contamination. The entire chamber is a tiny chip of silicon. As the reaction progresses, the team uses a fluorescent signal to analyze the DNA to determine whether it matches that of a particular subject.

LLNL has delivered one of these units to the Department of Defense

Figure 6. The Microtechnology Center's DNA analyzer and computer system fit in a briefcase. The polymerase chain reaction chamber and related analysis equipment are on the right side of the case.

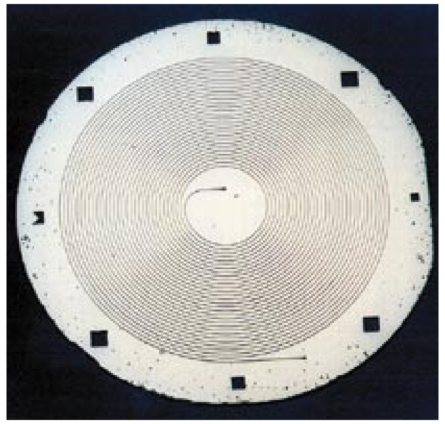

Figure 7. The column for the miniature gas chromatograph has been reduced to two silicon wafers bonded together. Here, one wafer is shown with its coiled groove 100 micrometers wide and several meters long.

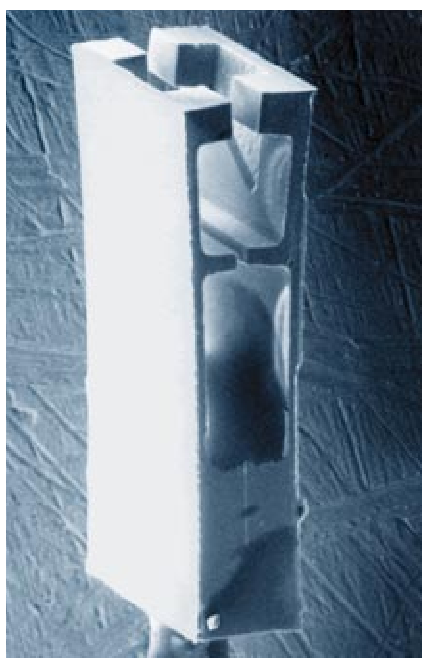

Figure 8. The microgripper, the size of two grains of salt, is the first in a series of new surgical microtools being developed by the Laboratory's Center for Healthcare Technologies.

Armed Forces Institute of Pathology, which is using it to quickly identify human remains in the field, test food and water for contamination in remote locations, and identify pathogenic bacteria on the battlefield.

The Microtechnology Center is also supporting the Laboratory's DNA sequencing work for the Human Genome Project. As described in the research highlight beginning on p. 18 of this issue, the Center has developed etched and bonded microchannel glass plates to speed up the sequencing process. A patent is pending on the new bonding process.

Conrad Yu of the Center is participating in work on a miniature, portable, low-power gas chromatograph to support the Laboratory's program in nonproliferation to counter the spread of chemical weapons. Gas chromatography is a proven method for identifying liquid or gas species, with detection sensitivities as high as parts per billion. Conventional gas chromatographs, however, are several cubic feet in size and typically take about 20 minutes to analyze a gas sample. A mini unit works faster, often requiring just one minute to complete an analysis, and would be very useful to carry into an area where chemical weapons or other poisonous gases are suspected to have been used. Someday this unit could also be used at home for sniffing out radon gas.

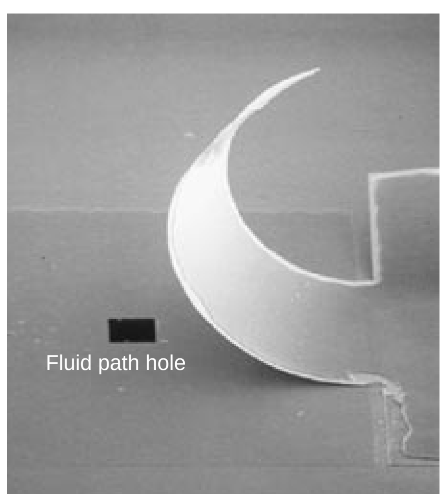

Figure 9. The 200-micrometer-long microvalve is shown in the open position, revealing an etched hole.

Yu has developed a micromachined, silicon sample injector about the size of a little fingernail. He has also reduced the size of the chromatograph's column where the various elements in the sample are separated before being directed to the detector where they are identified. The column has been reduced from 1.6 liters (100 cubic inches) for a laboratory-sized unit to a coil etched on a silicon wafer. A circular column 100 micrometers wide and several meters long is etched on two silicon wafers that are bonded together. The entire instrument occupies about 0.16 liter (10 cubic inches) (Figure 7).

Microtools for Better Health

A new surgical tool for treating aneurysms, the silicon microgripper is about the size of two salt grains—1 by 0.2 by 0.4 millimeters. With guidance from researchers at the University of California, San Francisco, Abraham Lee, M. Allen Northrup, and Peter Krulevitch developed this micro-electromechanical device. As shown in Figure 8, the microgripper is like a tiny hand that surgeons can use to place clot-inducing agents to fill an aneurysm. A surgeon may also use it to perform minimally invasive *in vivo* biopsy or catheter-based endovascular therapy. Nonmedical uses include assembling small parts for manufacturing and remote handling of small particles in extreme

environments, such as high or low pressures and hazardous fluids.

A key to the microgripper's effectiveness is a thin-film microactuator that is fabricated from a shape-memory alloy (SMA). At low temperatures, SMAs are easily deformed, but when heated, they recover their original shape. This reversible transformation forms the basis for shape-memory actuators, in which a biasing force, produced by a spring, for example, deforms the SMA element at low temperature, and the SMA element overcomes the bias when heated. For the microgripper, the team developed a sputter-deposited shape-memory actuator of nickel–titanium–copper, with a transformation temperature just above body temperature. The microgripper is inserted into a blood vessel in the closed (deformed) position. Through a thin wire connected to the microgripper, an electrical current of 0.1 milliamp activates the actuator, deflecting each arm up to 55 micrometers and returning the gripper to its undeformed (open) position. As it cools, the gripper will open again. (A patent was recently issued for another microgripper made of plastic with a balloon actuating system. It is briefly described on p. 23.).

Lee, Julie Hamilton, and Jimmy Trevino have also built a low-leakage, high-efficiency microvalve (Figure 9). Effective microvalves are an important link in creating miniature total analysis systems that can be used for drug delivery and bioanalytical instrumentation. Nonmedical applications for the microvalve include fluid injection analysis, chemical processing and analysis, and atmospheric and temperature control equipment. In this design, an electrode is sandwiched between two polyimide films with different coefficients of thermal expansion. (Polyimide is a flexible plastic material.) Delivery of less than 1 milliwatt of power causes the "cantilever" to clamp down, sealing an etched hole beneath it.

And the Work Goes On

Two relatively new areas of expertise for the Microtechnology Center are treaty verification and counterproliferation, which require low-cost, efficient, autonomous processing of large numbers of chemical and biological samples. Integrated microdevices are critical to the success of these new fields.

Microtechnologies and microdevices have never been an end in themselves at Livermore. Rather, they are problem solvers. As Lawrence Livermore researchers search for solutions to mission-specific challenges, they often find that commercial products do not meet their needs. They turn to the experts at the Microtechnology Center, whose creations are often what enable a Laboratory experiment or diagnostic tool to function successfully. Integrated microdevices are thus finding their way into increasing numbers of Laboratory projects.

— Katie Walter

Key Words: bioanalysis, DNA analysis, DNA sequencing, flow cytometry, gas chromatography, microactuators, microdevices, microstructures, photonics, polymerase chain reaction, semiconductors, shape-memory alloys, thin films.

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About the Scientist

RAY MARIELLA, JR., is head of the Microtechnology Center. For the last five years he has been a team leader for bioinstrumentation and the thrust area leader for microtechnology. Mariella joined Lawrence Livermore in 1987 as a project engineer in the Electronics Engineering Department's Engineering Research Division to establish a capability in molecular beam epitaxy. He received his B.S. in mathematics, chemistry, and chemical engineering from Rice University in 1969 and his M.A. and Ph.D. in physical chemistry from Harvard University in 1970 and 1973. Before coming to Livermore, he worked at the Allied Signal research facility in Morristown, Virginia. He has published more than 30 articles and holds 5 patents.